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Intermittent inland waters as important carbon sources

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评 述

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间歇性内陆水域是重要的碳源

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国家自然科学基金(41807366, 41673136, 41430753)、贵州省教育厅青年科技人才成长项目(黔教合KY字[2018]158)和2017年度贵州财经大学引进人才科研项目资助

摘要 内陆水域包括河流、溪水和湖泊、水库以及水池, 会部分出现暂时性或者季节性甚至年际性的干旱, 称之为间歇性内陆水域. 随着极端气候事件频发、人类活动加剧和土地利用变化等原因, 其面积不断增加. 然而, 内陆水域CO_2排放研究基本集中在常流水域, 对于间歇性水域的CO_2排放研究较少, 国内目前还未展开相关的工作. 本文综述了现今所知的包括河流溪水和湖泊水库以及水池在内的间歇性内陆水域在干旱和再浸润时CO_2排放, 讨论这两个阶段CO_2释放通量的控制因素和作用机理. 间歇性内陆水域在干旱时沉积物暴露接触到更多氧气, 有机质分解作用增强; 分解速率除受温度和湿度控制外, 还受上覆植被的影响, 存在时空差异性. 再浸润时发生类似土壤中"桦木效应", 间歇性内陆水域CO_2释放浓度迅速增加, CO_2排放通量受沉积物理化性质和温湿度影响. 最后估算间歇性内陆水域CO_2排放量为每年0.51 Pg C, 约占全球内陆水域CO_2(未计间歇性内陆水域)排放量的1/4, 是全球内陆水域重要的碳源. 因此, 计算全球内陆水域的CO_2排放量时, 应该把间歇性内水域考虑进去, 这将有助于更全面系统地了解区域和全球碳循环.

关键词 间歇性内陆水域, 干旱河床, CO_2排放量, 断流, 复流

内陆水域, 包括河流和湖泊(水库), 作为最活跃的物质循环和能量交换场所[1], 在全球碳循环中地位已变得无可争议[2]. 目前大部分研究仍集中在河流和湖泊(水库)向海洋输送的碳上[3~5], 而内陆水域与大气中的气体交换的研究较少[6~9]. 内陆水生生态系统可以像海洋一样, 通过光合作用固定无机碳, 以沉积物的形式累积大量的有机碳[10]. Raymond 等人[11]研究发现, 全球绝大部分水域中的$p$$CO_2$高于大气, 每年有2.1 Pg C从内陆水域中以$CO_2$气体的形式释放到大气中. 其中, 河流和溪水占到80%~90%(每年1.8 Pg C), 湖泊和水库以及水池只有10%~20%(每年0.3~0.5 Pg C)[11,12]. 间歇性河流和溪水(intermittent rivers and ephemeral streams, IRES)以及季节性干涸湖泊和水库并没有纳入内陆水域的范围(以下统称为间歇性内陆水域, intermittent inland waters, IIWS), 研究者认为他们"不够活跃"[13], 我们对这些时空不连续内陆水域的生物地球化学过程知之甚少[14,15]. 间歇性内陆水域在干涸之后, 大量CO_2从暴露于大气环境中的沉积物分解释放[16~20].

目前对全球内陆水域面积和分布的估算仍存在很多争议[21~23], 最新研究[23]表明, 全球的河流和溪水水域面积达到773000 ± 79000 km^2. Raymond等人[11]认为全球江河与溪水的面积分布与降水有很好的正相关关系, 而与温度呈弱负相关. Schneider等人[24]认为, 纬度在60°以下全球范围内有近30%的河流是间歇性的. Acuña等人[25]则认为已经超过半数, 在干旱和半干旱地区这一比例甚至更高, 最高达到69%[24], 且间歇性河流

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的面积随着全球变暖、人类过度抽取水资源和土地利用变化不断扩大[26,27]. 除河流之外, 在全球范围内存在很大一部分的水池和小面积湖泊会出现季节性干涸[28], 还有部分临海的浅水湖泊和水库受潮汐影响而出现大面积涨落[19], 一些内陆湖会因水源断流而出现永久性干涸[29]. 虽然内陆水域面积很小, 只占全球陆地非冰川覆盖面积的0.58% ± 0.06%[23]. 而且目前研究更多关注大流域, 小流量的水域经常被忽略[29~33]. 但这些因流量小而经常断流或季节性涨落的水域, 其生物地球化学过程极其活跃, 对全球的影响与面积不成比例[29,34]. 因此, 我们需要更加关注间歇性内陆水域, 包括CO_2的排放量.

季节性干旱水域环境中的碳排放(包括CO_2和CH_4等)研究主要集中在湿地[35]、水稻田[36]和泥炭地[37~39], 河流、湖泊和水库等因枯水期断流和丰水期复流出现时空上不连续水域的碳排放几乎完全被忽略. 主要是因为以下3个方面: (1) 间歇性内陆水域没有被划入水域环境又不被纳入陆地生态系统范畴[14]; (2) 间歇性内陆水域的面积很难估算, 且边界模糊, 特别是河流源头和散布的水池[24,26]; (3) 间歇性内陆水域气体交换通量测定受技术限制, 干旱暴露在环境中的沉积物空间异质性大, 碳排放通量估算存在困难[40,41]. 总地来说, 这些原因导致时空上不连续的间歇性内陆水域CO_2排放通量难以精确估算. 虽然在国际上已有研究者在开展相关方面的工作, 包括间歇性内陆水域的生物地球化学过程[42~44]和CO_2排放通量[13,45], 但国内在这一领域的研究仍处空白.

本研究综述了除湿地、水稻田和泥炭地等季节性干旱水域之外存在时空不连续性的水域(IIWS, 包括间歇性河流和溪水(IRES)、季节性干涸湖泊和水库)的CO_2气体排放. 主要分为两个过程: 一是河流断流和湖泊/水库干涸时沉积物暴露空气中释放CO_2通量激增, 二是断流河湖再被水淹没过程中沉积物分解释放CO_2爆发. 另外, 还有这两个过程在静水(湖泊、水库和水池)和流水环境(河流、溪水)中的差异性, 以及驱动这两个过程的不同环境控制因素并估算这几种间歇性内陆水域类型的CO_2排放量.

1 IIWS断流时的CO_2释放

1.1 干旱河床(DRBs)的概念和特征

IRES因断流而导致河床沉积物暴露, 国际上称为干旱河床[15], 包括湖泊和水库以及水池的季节性涨落区统称为DRBs(dry riverbeds). 干旱河床作为陆地生态系统、水生生态系统和两栖生态系统的群落交错区, 其研究价值逐渐被发现[15,45]. Larned等人[14]认为干旱河床的生物地球化学性质(包括CO_2的排放)远不及常年流水的河流与溪水活泼. 但最近的研究表明, DRBs中微生物分解活性很高, 有机质分解产生的CO_2通量不容忽视[46,47], 甚至有研究者认为这一排放通量远高于常流型河流, 与旱地土壤相当[13,48]. 尽管如此, DRBs的CO_2释放通量并没有被纳入全球陆地水域CO_2排放通量估算中[11].

与常流水域中的河床不同, DRBs在长时间没有水域淹没时, 表现出更多的“陆生性”而非“水生性”, 因此被一些研究者当作土壤来研究[49~51]. 但因为DRBs经过流水搬运沉积时经历了一系列的物理化学和生物作用, 同时又是陆生生态系统、水生生态系统和两栖生态系统的群落交错区, 直接将土壤科学中的理论和技术运用到干旱河床沉积物研究上来存在一定困难[52,53]. 在干旱的河道中, CO_2会通过生物作用有机碳(底栖微生物分解、细菌、真菌和菌根分解)过程从DRBs中释放[18,46,54]. 这些干旱的河道所释放的CO_2不能纳入陆地生态系统的碳排放是因为其已经被河流影响, 所以DRBs严格意义上不能算是陆地生态系统[14]. 除此之外, 河道的中DRBs具有不同于陆地土壤的理化性质和生物地球化学动态变化过程[14,15,55]. 因此, 准确揭示DRBs中的CO_2排放通量及其控制机理对区域乃至全球碳循环过程有重要意义.

1.2 DRBs暴露时的CO_2释放通量

然而, 目前对IIWS在断流时所释放的CO_2通量研究较少. 据报道的研究来看, DRBs的CO_2释放通量为4~1533 mmol m^{-2} d^{-1}[16~19,56,57], 平均100 mmol m^{-2} d^{-1}. 而这些明显高于已记录的湖泊和水库中的释放的CO_2通量(18~55 mmol m^{-2} d^{-1}, 平均38 mmol m^{-2} d^{-1})[11,58], 与河流(600 mmol m^{-2} d^{-1})[11]、干旱的泥炭地(150~213.6 mmol m^{-2} d^{-1}, 平均181 mmol m^{-2} d^{-1})[37]和土壤(−45.6~5262 mmol m^{-2} d^{-1}, 平均163 mmol m^{-2} d^{-1})[59]的CO_2释放通量在同一量级. Gómez-Gener等人[40]研究发现IIWS断流时的CO_2释放通量是平时流水期间的两倍, 而Sponseller[60]和Kosten等人[61]也发现在旱季沉积物的CO_2的释放通量也比淹水时期要高. Deshmukh等人[57]研究发现, 水库的DRBs在全年CO_2释放量甚至占

到总排放量75%．虽然目前对DRBs的CO_2释放通量研究较少，更多集中在地中海和澳大利亚等区域[16~19,59~61]，在亚洲包括中国对于DRBs中CO_2的释放通量的研究未曾有过报道．但从已有文献综合来看，IIWS在断流后干旱河床的CO_2释放通量远高于常流水域．

1.3 DRBs的CO_2释放控制因素

DRBs高CO_2释放通量的重要原因之一是丰富的有机质埋藏[62]，类似高度营养化的水池[63,64]．在土壤学研究中，土壤CO_2释放通量主要受土壤温度、湿度和土壤覆被所决定的供微生物分解有机质种类影响[65]．最近在关于DRBs的一些报道中，也发现了CO_2的释放速率与温度、湿度呈正相关，与有机质种类也相关[20,54]．另外还发现在曾经有沉水植物生长的水域，沉积物在暴露期间经过老化过程，更容易形成易分解的有机质[66]．在沉积物暴露之后，不管是否有植被生长，由于接触到更多的氧气，直接导致CO_2的释放量增加[67]．DRBs暴露的时间越长，沉积物中的湿度因蒸发而降低，有机质分解速率受到影响．但有研究表明，沉积物中的微生物胞外酶活性在DRBs暴露期间仍维持着一定的活度，保证有机质分解产生CO_2的速率[49,68,69]．Marxsen等人[46]的研究还表明，在IIWS断流时，DRBs下层区域(河床表层往下15 cm)的微生物分解活动和真菌微生物量要明显高于表层区域，这也可能是DRBs在暴露期间仍能在一段时间内保持高CO_2释放速率的重要原因．虽然DRBs的出现可能会导致微生物进入休眠甚至使得部分因干旱而死亡[70]，但Weise等人[71]和Jin等人[19]的研究发现，DRBs在暴露后包括酚类氧化酶和水解酶在内的微生物酶活性反而得到增强，沉积物分解产生更多的CO_2，这过程中CO_2的释放量是爆发性的增加．

DRBs的微生物分解除有机质活性能影响CO_2释放外，DRBs的类型也会影响CO_2的释放量．Gallo等人[18]发现不同类型的沉积物类型(砂砾型、沙土型和黏土型)在河流断流后CO_2释放通量存在较大差异，沙土型和黏土型是砂砾沉积物类型CO_2释放通量的30倍．Almeida等人[45]还发现，DRBs的CO_2释放通量由周围土地利用类型决定，其中林地是草地的两倍．温度是土壤CO_2释放的关键因素[72]，已有研究表明DRBs中温度对其影响只占27%~38%[18]．但温度对DRBs的CO_2释放过程影响以及控制机理目前报道甚少，有待进一步研究．

CO_2除了从有机质分解释放(主要是生物因素影响)，其他非生物成因如深部和基岩(特别是在碳酸盐地区)因周围环境条件发生改变，同样影响DRBs的CO_2释放．Marcé等人[73]发现，在河床暴露干旱期间，碳酸盐的溶解/沉淀导致了CO_2的释放量增加．另外，DRBs由于暴露时光照比有水淹没时强，因而其光降解产生的CO_2通量更高[74]．在不同环境中生物和非生物因素都可能会影响DRBs的CO_2的释放通量，谁占主导需要进一步深入的研究．

2 IIWS复流时的CO_2释放

2.1 “Birch effect(桦木效应)”的概念和特征

土壤干旱一段时间后，降水会改变土壤呼吸强度，在短时间内释放大量CO_2，在土壤学中称为“Birch effect”(桦木效应)[75]，这一现象在农田、草地、林地、泥炭地和荒漠中都广泛存在[76~79]．不同生态系统中，干旱后恢复湿度短时间内CO_2释放量有所不同．Sponseller[60]发现在荒漠生态系统中，恢复土壤湿度时其CO_2释放量是平时的30倍，48 h后恢复正常水平．Lee等人[80]则估算一次暴雨事件后，中纬度的森林生态系统每公顷土壤以CO_2的形式向大气中释放0.18 t C，占到全年净生产量的5%~10%．总地来说，因“桦木效应”，干旱土壤在降水后其CO_2释放量是平时的0.4~90倍[81~83]．“桦木效应”相关研究还没有在IIWS的沉积物中具体展开，但IIWS复流后DRBs因再浸润其CO_2的释放量表现明显上升趋势，包括在溪流[18]、河水[84]、水池[16]以及水库[51]等的间歇性内陆水域．DRBs暴露后因降水等原因而经过再浸润时，存在类似土壤中的“桦木效应”，IIWS会向大气中释放大量的CO_2．

2.2 DRBs再浸润时CO_2释放的决定因素与控制机理

DRBs再浸润导致CO_2爆发性释放的主要原因包括两个方面．一是决定微生物新陈代谢类型和强度的“反应底物”发生了变化．IIWS中的底栖生物(包括底栖微生物和底栖动物)和水生植物菌根等因DRBs沉积物在长时间暴露而死亡或进入休眠，与土壤环境中类似[85]．陆地生态系统，特别是森林生态系统，主要是以高C:N比的高等植被类型为主，富含木质素等难分解的物质[86]．IIWS生长的水生植物与陆地截然不同，除一些大型沉水植物外大都是低C:N比的低等植被类型[87]．DRBs再浸润后，底栖生物和低等植被的残体能迅速地

被分解[88]，CO_2释放量取决于残体类型和累积量，主要取决有效累积量[18,40]. DRBs沉积物在经过长时间暴露后，有机质中的团聚体分裂，更容易被微生物矿化分解[89]. 另外，DRBs沉积物中的颗粒孔隙因长时间暴露在空气中而被CO_2等气体填满，再浸润时水分渗透进入孔隙将CO_2等气体置换，释放填满孔隙中的CO_2等气体[90]. 此外，土壤中因为环境压力(比如气压)发生变化，造成文丘里效应[91]，影响CO_2的释放过程和释放通量[92]，但这在间歇性内陆水域中是否存在，目前还没有直接证据.

IIWS复流时CO_2释放过程除受DRBs沉积物的生物物理性质决定外，还受多种因子驱动. 首先是湿度，DRBs的湿度不仅影响IIWS断流时的CO_2释放，同时也会影响IIWS复流时的CO_2释放[93,94]，包括DRBs干旱时长、降水强度等[60,95]. 其次，IIWS频繁断流和复流会影响分解有机质的微生物群落稳定性，从而导致CO_2的排放通量减少[79,96]. 最后，人类活动的影响，包括改变DRBs的面积[15,97]，或在暴露的DRBs上堆放工业和生活垃圾而改变有机质的理化性质和含量[18,98]，会直接或间接地影响IIWS复流时的CO_2释放.

总地来说，IIWS断流和复流时CO_2的释放量受多重因素影响，既包括生物过程，也包括非生物过程，且时空异质性显著. 但CO_2释放通量远高于常流时的水面，如图1所示. 随着全球气候变化，极端天气事件频发，人类活动加剧和土地利用变化，IIWS的面积不断扩大[99]，CO_2排放量将会直接影响到大气中的CO_2浓度. 另外，内陆水域的沉积物，特别是湖泊沉积物在全新世的碳埋藏量非常大[5]，据估算达到了820 Pg C[100]，与地球其他重要储碳区(例如大气、土壤等)在同一量级[101]. 同时湖泊沉积物作为全球重要的埋藏碳汇[10]，每年捕获0.15 Pg C[62]. 因此，IIWS断流和复流不仅释放大量的CO_2进入大气成为碳源，还间接影响到内陆水域沉积物的有效碳埋藏，改变整个全球的碳循环过程.

2.3 IIWS断流和复流时的CO_2排放量

Schiller等人[13]最早对全球断流的河道CO_2排放量进行了估算，每年平均有0.3(0.2~0.7)Tg C释放，使全球河流的CO_2排放量增加0.4%~9%，但如果考虑复流时的CO_2排放，河流(包括IRES)中CO_2排放量提升20%以上(图1). 水库作为全球温室气体重要的释放源[12]，占人类CO_2排放量的近1.5%[58]. 虽然水位降落区域不到水库总面积30%(10%~28%)，但水库DRBs释放CO_2排放量却是常覆水面2倍[48]. 若将水位涨落区再浸润时CO_2释放量计算在内，水库DRBs的CO_2排放量是常覆水面的4倍以上(图1). 间歇性内陆水域断流和复流时CO_2排放量与其面积不成比例，在水库中表现尤为明显.

最新研究表明，全球的河水和溪流水域面积达到773000 km^2[23]. 根据Raymond等人[11]的公式计算，IIWS的面积将达到121623 km^2；而湖泊和水库的面积为3000000 km^2[11]，其DRBs面积将达到187542 km^2[27]；水池(小于900 m^2的水域)的面积为334366 km^2[28]，DRBs面积为18390 km^2[48]. 全球内陆水域面积存在时空动态上的变化，间歇性内陆水域也是如此. 不同类型的IIWS在断流和复流时CO_2的释放通量存在差异，根据已报道文献[16~19,48~51,102~104]中不同类型间歇性内陆水域DRBs干旱和再浸润时CO_2释放通量，分别取平均值后通过式(1)计算得到表1:

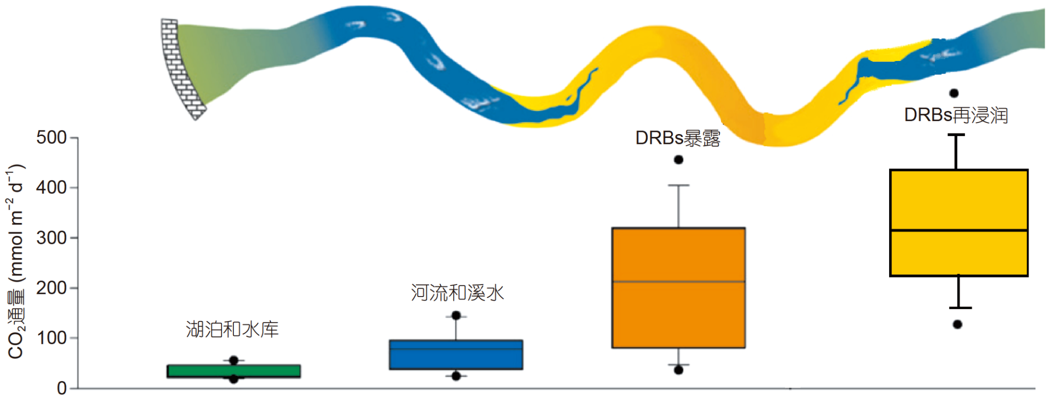

图 1 (网络版彩色)IIWS断流和复流过程以及CO_2释放通量示意图. 据Schiller等人[13]修改

Figure 1 (Color online) Comparison of CO_2 fluxes in IIWS drying and rewetting period. Modified from Schiller et al.[13]

表 1 全球IIWS断流和复流时CO_2排放通量

Table 1 Global estimate of CO_2 fluxes from IIWS

IIWS类型	年内累计断流和复流面积(km^2)	DRBs干旱时CO_2释放通量 ($mmol\ m^{-2}\ d^{-1}$)	DRBs再浸润时CO_2释放通量 ($mmol\ m^{-2}\ d^{-1}$)	全球的碳排放量 ($Pg\ C\ a^{-1}$)
河流与溪水	121623(本研究)	334(44~781)[48]	480(280~834, 本研究)	0.217(0.087~0.430)
湖泊和水库	187542[11,48]	320(216~515)[48]	377(84~659, 本研究)	0.286(0.123~0.482)
水池	18390[28,48]	148(10~600)[48]	121(20~526)[102]	0.011(0.001~0.045)
共计	327555			0.514(0.211~0.955)

$$C_{\rm IIWS}=F_{\rm d}\times A\times T_{\rm d}+F_{\rm r}\times A\times T_{\rm r}, \tag{1}$$

其中, $C_{\rm IIWS}$为间歇性内陆水域CO_2排放量; $F_{\rm d}$为不同类型间隙性内陆水域干旱暴露时CO_2释放通量; $T_{\rm d}$为干旱时长; $F_{\rm r}$为不同类型间歇性内陆水域干旱再浸润时CO_2释放通量; $T_{\rm r}$为再浸润时长; A为不同类型间歇性内陆水域面积.

IIWS在断流和复流时的CO_2全球排放为每年0.51 (0.21~0.96)Pg C, 是Raymond等人[11]估算的全球内陆水域(不包括间歇性内陆水域)CO_2排放量2.1(1.56~2.94) Pg C的24%. 然而, IIWS的面积只占全球内陆水域的8%, 但因IIWS断流和复流时的CO_2排放量是常流水域的近1/4, 由于受全球气候变化、人类活动和土地利用改变等因素的影响, 间歇性内陆水域的CO_2排放量还会增加. 由此可见, IIWS在全球内陆水域碳循环过程发挥重要作用, 应该把IIWS断流和复流时的CO_2排放计入全球碳排放中.

3 研究展望

IIWS作为全球内陆水域的一部分, 在估算全球内陆水域的CO_2排放时, 并没有将其计算进来[11]. 虽然已经有越来越多的研究者开始注意到DRBs暴露时沉积物分解释放CO_2释放过程, 包括河流[15]、溪水[40]、湖泊和水库[5]以及水池[20]. 但是精确计算IIWS断流和复流时CO_2的排放量和控制机理等方面的研究仍显不足, 气候变化、土地利用调控和岩石风化(特别是碳酸盐风化)[105]产生的不同反馈机制对IIWS断流和复流时CO_2释放过程和全球碳源-汇平衡的影响还未考虑. 主要从以下4个方面对IIWS的CO_2释放过程和排放量研究进行展望.

3.1 IIWS面积的准确估算

水域面积的准确估算目前仍然是我们研究内陆水域CO_2排放量面临的一个挑战. IIWS由于存在断流和复流, 水域面积在时空上不连续, 存在季节和年际变化, 甚至显著昼夜变化; 另外一些流量较小的河流和溪水以及河源汇流, 受气候变化影响容易断流和复流. 随着遥感和高分辨率卫星等技术的发展, 全球水域面积估算变得更精确[23,27], 如Keys等人[106]通过湖泊和水库的水位变化准确掌握了湖泊和水库面积的时空动态变化, 也有科学家对IIWS面积时空变化进行粗略估算[11,13]. 但考虑到前述原因, IIWS面积(特别是小流量河流和散布水池以及河流源头等水域面积)的精准估算依然是目前研究IIWS中CO_2排放甚至全球碳循环过程的关键.

3.2 DRBs的CO_2释放通量测定

精准估算IIWS的CO_2排放量除了要获取水域面积, 另外一个关键问题是精确测定IIWS在断流和复流时的CO_2释放通量. 目前常流水面的CO_2释放通量测定主要通过浮式静态箱法[107,108]直接测定, 或基于水文地貌平衡方程进行计算[32,109]来间接获取, 这些方法都各有优缺点[110]. 对于IIWS断流时DRBs暴露的CO_2释放通量, 研究者也采取了间接计算[18]和直接测定[61]的方法来获得. DRBs再浸润时的CO_2释放通量目前只有间接计算[40,111], 没有直接测定, 存在较大的误差, 不能直观表现时空动态变化. 另外, IIWS复流时DRBs从干旱转变为湿润, 最后到浸没状态, 静态箱法在直接测定其动态变化过程中CO_2通量上存在技术难度, 目前直接测定DRBs再浸润时CO_2释放通量未曾报道. 此外, 静态箱法在测定水面(或者DRBs)的CO_2释放通量的最大问题是容易丢失释放气体的峰值[112], 而IIWS在断流和复流时CO_2释放通常是爆发性多峰释放[61], 特别是在断流和复流前期, 导致容易低估IIWS的CO_2排放通量. 针对这一问题, 利用涡度协方差法(eddy covariance)的高分辨率和高精度连续监测可能是直接测定IIWS断流和复流时CO_2释放通量的最佳方法, 或者多种方法联用(涡度协方差的高分辨率获得多点间歇性内陆水域在断流和

复流CO_2连续释放通量，拟合间接计算CO_2释放通量，建立区域和全球模型，准确估算区域和全球间歇性内陆水域CO_2释放通量)，这还需要进一步的研究.

3.3 DRBs释放CO_2的控制机理

IIWS在断流和复流时CO_2溢出，主要是沉积物分解释放CO_2的过程，不管是生物作用还是非生物过程引起. 全球内陆水域中的沉积物分为外源和内源，外源沉积物会更多地继承土壤的特点，外源为主的DRBs沉积物可以从土壤学角度来进行研究，包括DRBs干旱暴露和再浸润时的CO_2释放以及控制机理[113]，但需要谨慎对待. 而内源为主的DRBs沉积物，主要是水生植物新代谢累积埋藏[114,115]，内源有机质与外源有机质特征存在较大差异[116]，直接导致CO_2在DRBs暴露和再浸润时释放的环境条件不同(例如有机质分解耗能阈值)，对CO_2释放过程和排放通量产生影响. 因此，DRBs在干旱暴露以及再浸润过程中，区分沉积物不同来源的类型对研究有机质分解释放CO_2的控制机理可能是一个重要研究方向. 另外，DRBs暴露和再浸润时CO_2多峰释放作用机理和这过程中微生物群落组成变化并不清楚，也是未来的研究重点.

3.4 IIWS的CO_2排放与全球碳循环

准确估算IIWS的CO_2排放量和DRBs释放CO_2的控制机理只是深入了解间歇性内陆水域在区域和全球碳循环角色的第一步. 工业革命以来，人类活动对全球碳循环的影响和潜在反馈机制对大气CO_2浓度变化响应是未来重要研究主题[117]. IIWS碳排放对全球碳循环的收支过程和反馈机制的影响仍不清楚，意味着考虑气候变化和土地利用调控对间歇性内陆水域时空变化、DRBs沉积物特征的影响值得进一步的思考和探索.

总之，IIWS作为内陆水域中不可忽视的一部分，在断流和复流时CO_2排放是全球内陆水域(未计间歇性内陆水域)CO_2排放量的1/4，但IIWS面积只占到全球内陆水域面积的8%，与其CO_2排放量不成比例，是全球重要的碳源. 截至目前，国内还未有报道开展IIWS的CO_2排放和相关生物地球化学过程的工作，仍属于研究空白. 因此，开展间歇性内陆水域相关的研究工作，不论在过去、现在还是未来对区域和全球碳循环都有重要意义.

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Summary for “间歇性内陆水域是重要的碳源”

Intermittent inland waters as important carbon sources

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A large part of the world’s inland waters, including streams, rivers, ponds, lakes, and reservoirs is subject to occasional, seasonal, or even permanent drying. Moreover, the intermittent inland waters are increasing in many areas of the world because of climate change, anthropogenic influence, and land-use change. However, information on the carbon dioxide (CO_2) fluxes from intermittent inland waters is scarce. Thus, a comprehensive assessment of CO_2 emissions in intermittent inland waters is necessary and is a research gap in China. Here, we review the current knowledge on CO_2 fluxes from lotic (streams and rivers) and lentic (ponds, lakes, and reservoirs) inland waters during dry and rewetting phases, considering controls and sources as well as implications of the two phases for local and global scale estimates. In exposed sediments of dry riverbeds, it can be a long time between wet and dry conditions. At the onset of drying, the increased oxygen availability can stimulate enzymatic activities and overall microbial growth, leading to an increased breakdown of organic matter and the subsequent release of CO_2. As in any ecosystem, carbon emissions derive from a set of abiotic and biotic sources, the relative importance of which is tied to intrinsic features, such as geology, microbial communities and available organic substrates, and environmental controls, such as moisture and nutrient availability. Besides microbial respiration, geologic carbon can be a relevant source of CO_2 emissions. Particularly in carbonate-rich regions, photodegradation of organic matter on dry light-exposed sediments can also lead to increased CO_2 losses. In addition, covered vegetation metabolism, including photosynthesis and respiration, can be a relevant part of dry riverbed sediment CO_2 emissions. Short rewetting episodes can trigger microbial respiration and CO_2 release from the exposed sediments, and marked increases in the CO_2 flux from dry sediments are to be expected during rewetting after a dry period, similar to soils, and it is known as the Birch effect. Immediately after rewetting, gases in pore spaces are displaced by water, potentially causing a significant efflux of CO_2, impacting the overall annual CO_2 flux. Rewetting events can also cause the remobilization of organic matter and nutrients. At the micro-scale, pore-filling will increase the dissemination of water-soluble substrates and mobilize labile substances from dead biomass. Aggregate disruption and the destabilization of organic-mineral complexes will also liberate carbon otherwise protected from microbial action. Other major drivers of CO_2 fluxes from dry riverbeds include the presence or absence of vegetation or micro-phyto benthos in the exposed sediments, sediment texture, sediment temperature, and sediment organic matter. The organic matter quantity may be more important than the quality in controlling the magnitude of CO_2 fluxes from the exposed sediments. Our conservative estimates indicate that adding emissions from intermittent inland waters to current global estimates of CO_2 emissions from inland waters could result in an increase of 0.51 Pg C a^{-1} or ~1/4 of total fluxes. Therefore, intermittent internal waters should be considered when estimating the CO_2 emissions of global inland water. Future investigations should focus on the in-depth study of the main sources of uncertainty involved in carbon emissions from intermittent internal waters to understand the physical and biological mechanisms behind this flux, and the impact on the global carbon cycle. Important study topics include: (1) Accurate estimation of the area of intermittent inland waters, in particular, the area of small-flow rivers, scattered ponds, and the area of headwaters; (2) CO_2 efflux measurement of dry riverbeds, including the determination of CO_2 efflux directly and indirectly, and combining the two methods; (3) the mechanism of CO_2 release from dry riverbeds and factors driving CO_2 fluxes from intermittent inland waters, such as the ratio of autochthonous and allochthonous carbon in sediments during dry and rewetting episodes; and (4) deep understanding of the changes in extension and seasonality of intermittent internal waters, particularly those in response to climate oscillations, land-use changes, and potential feedback related to climate at decadal time-scales. The results from these additional studies will help explain completely the inland water carbon emissions and identify potential implications for regional and global carbon cycles.

intermittent inland waters, dry riverbeds, CO_2 emissions, dry phase, rewetting phase

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